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ABSTRACT
An accidental or intentional outdoor release of pollutants can produce a hazardous plume, potentially contaminating large portions of a metropolitan area as it disperses downwind. To minimize health consequences on the populace, government and research organizations often recommend sheltering in place when evacuation is impractical. Some reports also recommend "hardening" an indoor shelter, for example by applying duct tape to prevent leakage into a bathroom. However, few studies have quantified the perceived beneficial effects of sheltering and hardening, or examined the limits of their applicability. In this paper, we examine how sheltering and hardening might reduce exposure levels under different building and meteorological conditions (e.g., wind direction). We predict concentrations and exposure levels for several conditions, and discuss the net benefits from several sheltering and hardening options.

INDEX TERMS
Airflow modeling, Shelter-in-place, COMIS, Exposure, Emergency response

INTRODUCTION
Catastrophic releases of pollutants outdoors can lead to significant population exposures. There are two general response options: shelter-in-place or evacuation. The latter is not regarded as practicable in many circumstances, especially in urban areas where population densities limit rapid and efficient evacuation, while the effectiveness of the former is not well studied. In some cases, hardening the sheltering zone, such as a bathroom, by applying duct tape to seal cracks and other leaks has been recommended (e.g., Sorensen and Vogt, 2001).

For a non-reactive gas, individuals indoors will eventually receive the same time-integrated concentration as those outdoors, irrespective of sheltering and hardening procedure, if the indoor air exchange remains constant. This implies that the ideal response is to shelter while the outdoor concentration is greater than the indoor concentration, and to exit the building after the plume passes (Chan et al. 2004). However, current assessments of exposure for sheltering occupants largely ignore whether specific building details, meteorological conditions, or any occupant intervention can improve the degree to which sheltering in place reduces exposures to individuals.

In this paper, we demonstrate that some sheltering and hardening strategies may have important net benefits to the overall exposure of individuals. We predict exposure for various building and environmental conditions (e.g., wind direction), analyze the effectiveness of

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hardening measures, such as sealing doors or windows with a wet towel, and provide recommendations for pre-event planning.

Note that this paper does not consider physical processes, such as deposition or sorption, that reduce indoor concentrations relative to those outdoors. Nor does it consider the effect of toxic load, in which critical exposure to an agent depends on the peak concentration as well as on the time-integrated concentration. These important effects reduce health consequences in buildings, regardless of the shelter-in-place strategy.

MODEL SETUP

As our case study, we developed a computer simulation of an idealized outdoor gaseous plume passing over a hypothetical single-floor house. We assumed that the outdoor plume is essentially Gaussian and is driven by a 3 m/s uniform wind. For these purposes, we also assumed that the plume 'enveloped' the house uniformly – that is, the outdoor concentration profile was the same at all locations around the house.

We used the COMIS multizone airflow software package (Feustel, 1999) to predict airflow and pollutant dispersion into and within the house. COMIS predicts the steady-state flow of air induced by wind, thermal buoyancy, and mechanical ventilation. Air flows between zones via flow paths, such as cracks, door and window leaks, and ductwork. Air is assumed incompressible, and airflow through these pathways is calculated by balancing pressure differences between the zones. We refer the reader to Feustel (1999), Lorenzetti (2002), and Sohn et al. (2003) for descriptions of the model and for relevant applications.

Figure 1 shows the floor plan of the hypothetical house. For this demonstration, we configured the floor plan to consist of a bathroom, (an often-recommended sheltering location), and the remainder of the building, which we call the "living area." The rationale for this simplified approach is that, for this study of the effects of hardening a single room within a hypothetical residence, the assumed details of the other rooms introduce needless complication. Accordingly, we assumed that, with interior doors open (for all but the bathroom), transport within the interior is reasonably uniform over the time periods of interest.

We developed a model of the building in COMIS and specified leakage parameters through cracks and windows. We set the leakages so that the net indoor – outdoor air exchange was approximately 0.75 air changes per hour under no hardening conditions. The crack size on each wall is approximately equal; in the case of the wall containing the bathroom, the crack distribution is apportioned by surface area between the two wall segments.

We predicted the indoor concentrations for several building conditions and two wind directions. Figure 2 shows the concentration profile for the outdoor plume as it passes the building. The figure also shows the ensuing interior distribution of the pollutant for the case of a North wind. In this example, we hardened the door between the living area and the bathroom by reducing the original door leakage by 90%. Such a reduction could result from placing a wet towel under the door to cover the gap below the door.

The peak bathroom concentration is predicted to be two orders of magnitude less than in the living room. In the case of an ideal response (as defined above), an occupant in the living room would exit the building at ~50 minutes after the plume reaches the building, when the outdoor concentration is less than the living room concentration. An occupant in the bathroom, on the other hand, would exit at ~100 minutes, at a much lower concentration.

We also predicted interior concentrations if the outdoor plume was driven by a South wind. With the bathroom on the south side of the building, this provides a contrasting situation where the importance of the different leakage paths may change.

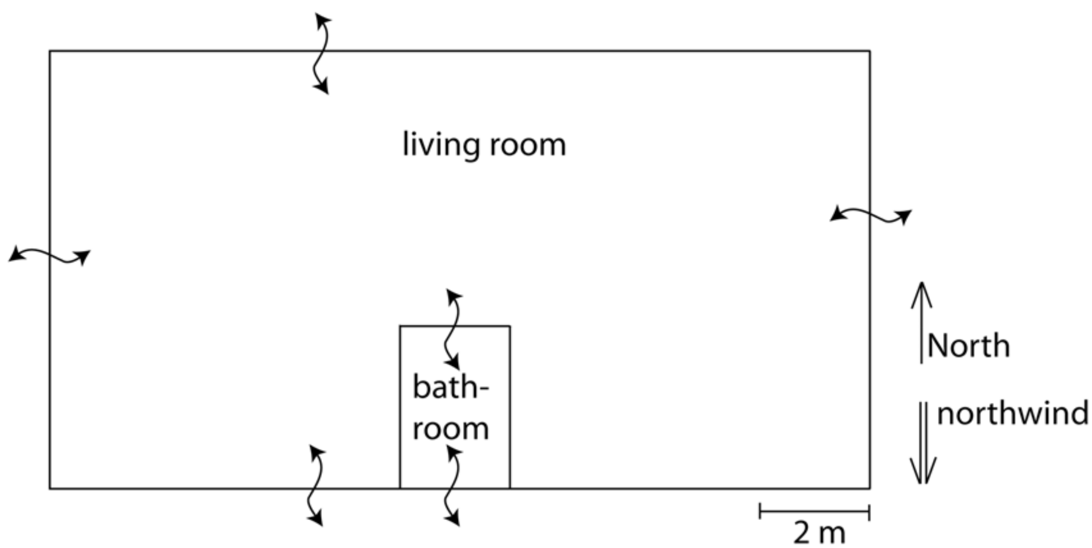

Figure 1. Floor plan of the case study building. The curved arrows represent flow pathways through leaks and cracks. The double arrow defines the wind direction.

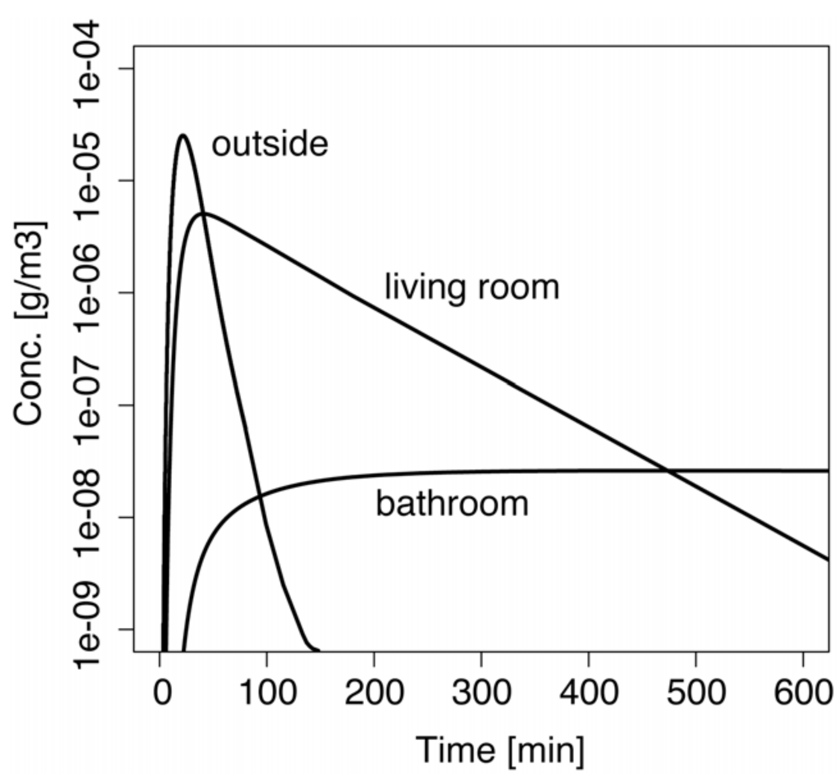

Fig. 2. Concentration predictions for a 3 m/s North wind. In this figure, the door between the living room and the bedroom is assumed to be hardened by inserting a wet towel underneath the door.

RESULTS
We predicted indoor pollutant dispersion and exposure for occupants sheltering in the bathroom. In figure 3, we show the ratio between exposure to an individual sheltering in the bathroom to exposure to an individual outdoors, for a plume approaching the building from the South side of the building. Hardening the bathroom door or window refers to reducing the leakage size to 90% of its original, unhardened, leakage.

Figure 3 shows that without hardening the bathroom door or window (solid line), an individual sheltering in the bathroom will eventually suffer the same time-integrated exposure as an individual outdoors (i.e., after about 150 minutes). In this case, both individuals will observe equivalent adverse health endpoints if the toxicity of the agent is linear to concentration. If toxicity is not linear to concentration, individuals sheltering indoors typically will have lower adverse health endpoints, due to the lower peak concentration (ten Berge, 1986).

Figure 3 also shows that hardening the bathroom door or window substantially reduces exposure. In this scenario, hardening the door reduces exposure more than hardening the window, even though the outdoor plume approaches the south-facing wall. One might expect that hardening the window would reduce the amount of agent entering the bathroom window. However, in the unhardened case, the window already serves as the limiting airflow resistance for the bathroom. Therefore restricting the door crack reduces the infiltration into the bathroom much more effectively than does reducing the window leakage (leaks in buildings have highly nonlinear pressure-flow relations, and do not simply sum in series).

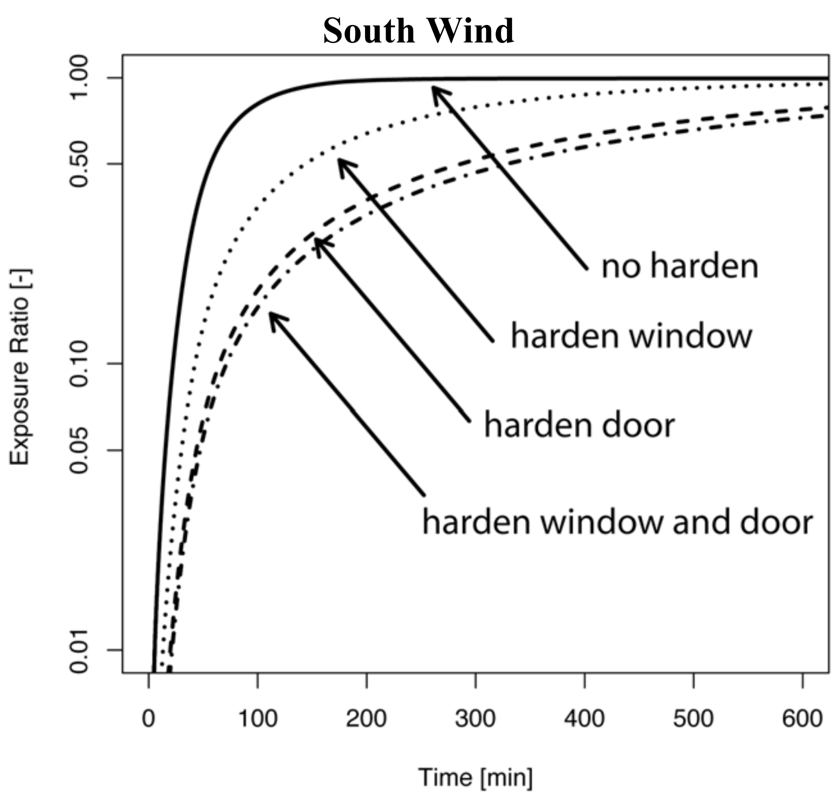

Figure 3*. Ratio of exposure to an individual sheltering in the bathroom to an individual outdoors. Note that the y-axis is plotted on a log scale.*

Figure 4 shows the same exposure ratios for a plume approaching the building from the north. Wind blowing on the north wall causes air to flow from the living area through the bathroom and out the bathroom window. Hardening the door restricts the amount of air flowing from the living area to the bathroom, and thus reduces the concentration in the bathroom. While eventually the exposure in the hardened bathroom will reach the same value as the unhardened case, figure 4 shows that hardening buys considerable time before this happens. Thus for this simple building model, having the shelter downwind reduces the importance of uncertainty when to exit the shelter, in terms of reducing the time-integrated exposure.

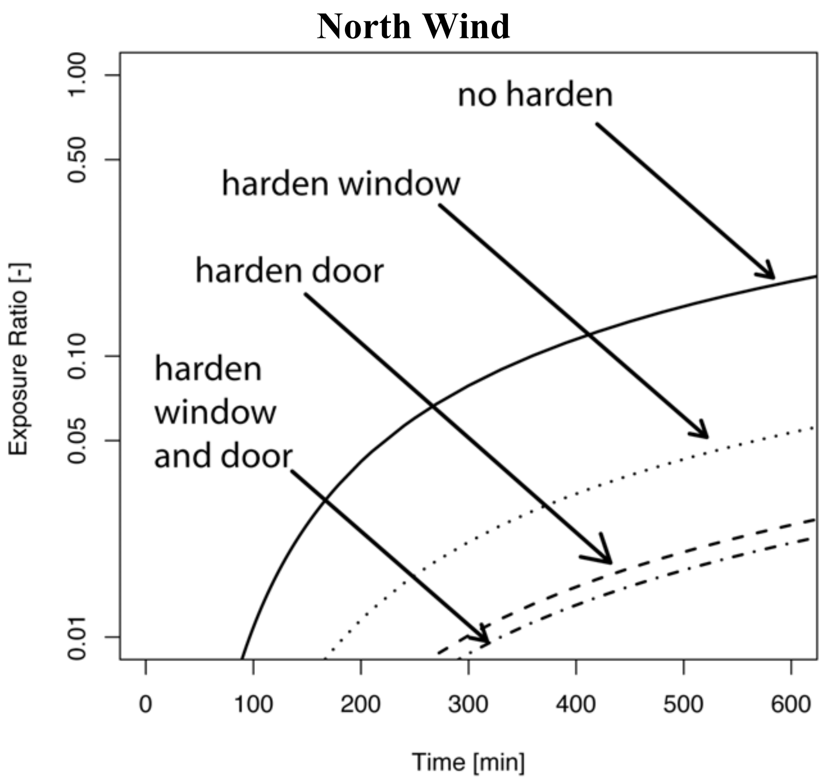

***Figure 4**. Ratio of exposure to an individual sheltering in the bathroom to an individual outdoors. The concentration predictions for the harden bathroom door condition is plotted in Figure 2. Note the y-axis is plotted on a log scale.*

DISCUSSION AND CONCLUDING REMARKS

We present here an illustrative example of the types of considerations that enter into recommending sheltering-in-place as a means of reducing exposures to an outdoor plume. Though sheltering is always likely to be one of the most feasible and effective responses to an outdoor plume, its utility may be improved considerably by choice of effective strategies. We found that hardening can dramatically reduce occupant exposure, provided it is paired with an ideal exit strategy (alternately, hardening buys more time in the shelter, in case it is not known exactly when the outdoor plume has passed). We also found that identifying the paths of least resistance in the flow network may help in creating an effective shelter. It may be that sealing the big holes is more important. In this example, sealing the larger leakage between the bathroom and the living area will have a better effect no matter what the direction of the wind. Further study and statistical analysis of wind direction for other generic building configurations may help us better determine if and what generic sheltering and hardening conditions should be considered.

ACKNOWLEDGEMENTS
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